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Signatures of anomalous couplings in boson pair production through $\gamma\gamma$ collisions [1]

G.J. Gounaris[a], J.Layssac[b] and F.M. Renard[b]

[a]Department of Theoretical Physics, University of Thessaloniki,
Gr-54006, Thessaloniki, Greece,

[b]Physique Mathématique et Théorique, CNRS-URA 768,
Université de Montpellier II, F-34095 Montpellier Cedex 5.

Abstract

We discuss possible New Physics (NP) effects on the processes $\gamma\gamma \to W^+W^-$, ZZ, $Z\gamma$, $\gamma\gamma$, HH which are observable in $\gamma\gamma$ collisions. Such collisions may be achieved through laser backscattering at a high energy e^+e^- linear collider. To the extent that no new particles will be directly produced in the future colliders, it has already been emphasized that the new physics possibly hidden in the bosonic interactions, may be represented by the seven $dim = 6$ operators $\mathcal{O}_W$, $\mathcal{O}_{B\Phi}$, $\mathcal{O}_{W\Phi}$, $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$ (the last two ones being CP-violating). In this paper, we show that the above processes are sensitive to NP scales at the several TeV range, and we subsequently discuss the possibility to disentangle the effects of the various operators.

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1 Introduction

The search for manifestations of New Physics (NP) is part of the program of future high energy colliders [1, 2]. As discussed in previous papers [3, 4, 5], if no new particles are produced in the future colliders, these NP manifestations may appear only as anomalous interactions among the particles already present in SM. In this paper we restrict to the study of the purely bosonic part of such forms of NP [3, 4, 6]. Within a framework like this, NP effects have been searched for by using the high precision measurements obtained at LEP1 [7]. High energy e^+e^- linear colliders will offer many more possibilities though, to test the sector of the gauge boson and Higgs interactions with a high accuracy. The most famous process is $e^+e^- \to W^+W^-$ [8]. This has been carefully studied and it has been shown that indeed the 3-gauge boson vertices γW^+W^- and ZW^+W^- can be very accurately constrained through it [9, 10].

Another type of processes accessible at a linear collider is boson-boson scattering [11]. Such processes are even more interesting, since they are sensitive not only to the 3-gauge boson vertices, but also to 4-gauge boson [12, 13, 14] as well as to Higgs couplings [15]. Thus the scalar (Higgs) sector, which is presently the most mysterious part of the electroweak interactions, may be tested in a much deeper way using the $\gamma\gamma$ collisions offered by the laser backscattering method [16].

In a $\gamma\gamma$ collider, the five boson pair production processes available to be studied are $\gamma\gamma \to W^+W^-$, ZZ, $Z\gamma$, $\gamma\gamma$ and HH (assuming that the physical Higgs particle exists and it is not very heavy). The purpose of the present work is to show that the study of the p_T distribution of one of the final bosons provides a very sensitive test of the various possible forms of NP. At present we leave aside the process $\gamma\gamma \to H$, which indeed provides a very powerful way to study the anomalous couplings of the Higgs particle. This single Higgs production process has been first considered in [15] and is thoroughly trated in the companion paper [17]. In the present paper we concentrate on the boson pair production due to both gauge and Higgs boson exchanges. The specific illustrations we give assume a Higgs mass in the 100 GeV region.

Assuming that the NP scale Λ_{NP} is sufficiently large, the effective NP Lagrangian is satisfactorily described for our purposes in terms of $dim = 6$ bosonic operators only [18, 4]. There exist only seven $SU(2)\times U(1)$ gauge invariant such operators called "blind", which are not strongly constrained by existing LEP1 experiments [3, 4, 6]. Three of them

$$\mathcal{O}_W = \frac{1}{3!}\left(\overrightarrow{W}_\mu{}^\nu \times \overrightarrow{W}_\nu{}^\lambda\right)\cdot \overrightarrow{W}_\lambda{}^\mu \quad , \tag{1}$$

$$\mathcal{O}_{W\Phi} = i\,(D_\mu\Phi)^\dagger \overrightarrow{\tau}\cdot \overrightarrow{W}^{\mu\nu}(D_\nu\Phi) \quad , \tag{2}$$

$$\mathcal{O}_{B\Phi} = i\,(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \quad , \tag{3}$$

induce anomalous triple gauge boson couplings, while the remaining four[2]

$$\mathcal{O}_{UW} = \frac{1}{v^2}(\Phi^\dagger\Phi - \frac{v^2}{2})\,\overrightarrow{W}^{\mu\nu}\cdot\overrightarrow{W}_{\mu\nu} \quad , \tag{4}$$

$$\mathcal{O}_{UB} = \frac{4}{v^2}\,(\Phi^\dagger\Phi - \frac{v^2}{2})B^{\mu\nu}\;B_{\mu\nu} \quad , \tag{5}$$

$$\overline{\mathcal{O}}_{UW} = \frac{1}{v^2}(\Phi^\dagger\Phi)\,\overrightarrow{W}^{\mu\nu}\cdot\overrightarrow{\widetilde{W}}_{\mu\nu} \quad , \tag{6}$$

$$\overline{\mathcal{O}}_{UB} = \frac{4}{v^2}\,(\Phi^\dagger\Phi)B^{\mu\nu}\;\widetilde{B}_{\mu\nu} \tag{7}$$

create anomalous CP conserving and CP violating Higgs couplings. These later four operators constitute a dedicated probe of the scalar sector. Ideas on how these operators could be generated in various NP dynamical scenarios have been discussed in [6, 19]. The effective Lagrangian describing the NP induced by these operators is given by

$$\begin{aligned}\mathcal{L}_{NP} = {} & \lambda_W\frac{g}{M_W^2}\mathcal{O}_W + \frac{f_B g\prime}{2M_W^2}\mathcal{O}_{B\Phi} + \frac{f_W g}{2M_W^2}\mathcal{O}_{W\Phi} \quad + \\ & d\;\mathcal{O}_{UW} + \frac{d_B}{4}\;\mathcal{O}_{UB} + \overline{d}\;\overline{\mathcal{O}}_{UW} + \frac{\overline{d}_B}{4}\;\overline{\mathcal{O}}_{UB} \qquad ,\end{aligned} \tag{8}$$

which fully defines the various couplings. Quantitative relations between these couplings and the corresponding NP scales have been established on the basis of the unitarity constraints [20, 21, 6].

Below, we first write the amplitudes for the five processes mentioned above, in terms of the seven couplings associated to the operators considered. We then discuss procedures towards disentangling the effects of these operators. This allows us to express the observability limits for the various forms of new physics, in terms of the related NP scales. We find that this can be achieved to a large extent by just using only the aforementioned p_T distribution. Only for the disentangling of the CP violating operators it is necessary to augment this simple analysis by also looking at the density matrix of the final W or Z bosons.

In Sect. 2 we recall the formulation of $\gamma\gamma$ collisions through the laser backscattering method and give the expressions for the luminosities and the invariant mass and p_T distributions. These distributions are expressed in terms of helicity amplitudes most of which are computed in [22, 15, 21]. In Appendix A we just give the analytic expressions for their NP contributions in the high energy limit. Sect. 3 contains an overview of the characteristics of each of the five $\gamma\gamma$ processes, emphasizing their dependence on the various anomalous couplings. The precise sensitivity to each operator is discussed in Sect. 4 and the possible ways to disentangle them in Sect. 5. Concluding words are given in Sect. 6.

[2]In the definition of $\mathcal{O}_{UW}$ and $\mathcal{O}_{UB}$ we have subtracted a trivial contribution to the W and B kinetic energy respectively.

2 Laser induced $\gamma\gamma$ collisions

The boson pair production processes that we shall consider here are $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to ZZ$, $\gamma\gamma \to \gamma Z$, $\gamma\gamma \to \gamma\gamma$, and also $\gamma\gamma \to HH$.

In laser induced $\gamma\gamma$ collisions at e^+e^- colliders, with unpolarized $e^\pm$ and laser beams, photon fluxes are given in terms of the photon distribution

$$f_{\gamma/e}^{laser}(x) \;=\; \frac{1}{D(\xi)}\left(1-x+\frac{1}{1-x}-\frac{4x}{\xi(1-x)}+\frac{4x^2}{\xi^2(1-x)^2}\right) \quad , \tag{9}$$

where x is the fraction of the incident $e^\pm$ energy carried by the backscattered photon, and

$$D(\xi) = \left(1-\frac{4}{\xi}-\frac{8}{\xi^2}\right) Ln(1+\xi) \;+\; \frac{1}{2}+\frac{8}{\xi} \;-\; \frac{1}{2(1+\xi)^2} \quad , \tag{10}$$

with $\xi = 2(1+\sqrt{2}) \simeq 4.8$, $x_{max} = \frac{\xi}{1+\xi} \simeq 0.82$ [23, 24].

The invariant mass distribution is obtained as

$$\frac{d\sigma}{dy} \;=\; \frac{d\mathcal{L}_{\gamma\gamma}}{dy}\,\sigma_{\gamma\gamma}(s_{\gamma\gamma}) \qquad , \tag{11}$$

where

$$\frac{d\mathcal{L}_{\gamma\gamma}(y)}{dy} \;=\; 2y\int_{\frac{\tau}{x_{max}}}^{x_{max}} \frac{dx}{x} f_{\gamma/e}^{laser}(x)\, f_{\gamma/e}^{laser}\left(\frac{\tau}{x}\right) \qquad , \tag{12}$$

and

$$y \equiv \sqrt{\tau} \;\equiv\; \sqrt{\frac{s_{\gamma\gamma}}{s_{ee}}} \tag{13}$$

is the ratio of the $\gamma\gamma$ c.m. energy to the e^+e^- one satisfying

$$y < y_{max} \;\equiv\; x_{max} \simeq 0.82 \quad . \tag{14}$$

The correspondingly expected number of events per year is

$$\frac{dN}{dy} \;=\; \bar{\mathcal{L}}_{ee}\frac{d\sigma}{dy} \qquad , \tag{15}$$

where $\bar{\mathcal{L}}_{ee}$ is the integrated e^+e^- annual luminosity taken to be $20, 80, 320 fb^{-1} year^{-1}$ for a 0.5, 1. or 2. TeV collider respectively.

Of course, forward boson production should be cut-off in a realistic situation, since these events are inevitably lost along the beam-pipe. An efficient way of doing this is by looking at the transverse-momentum distribution of one of the final bosons B_3 and B_4 and cutting-off the small p_T values. For a fixed invariant mass of the final boson pair, this is given by

$$\frac{d\sigma}{dp_T dy} \;=\; \frac{y p_T}{8\pi s_{\gamma\gamma}|\Delta|}\int_{\frac{\tau}{x_{max}}}^{x_{max}} dx f_{\gamma/e}^{laser}(x)\, f_{\gamma/e}^{laser}\left(\frac{\tau}{x}\right) \Sigma|F(\gamma\gamma \to B_3B_4|^2 \;, \tag{16}$$

where

$$|\Delta| \;=\; \frac{1}{2}\sqrt{s_{\gamma\gamma}(s_{\gamma\gamma}-4(p_T^2+m^2))}\;\;, \tag{17}$$

$$p_T^2 \;<\; \frac{s_{\gamma\gamma}}{4}-m^2\;\;, \tag{18}$$

and $F(\gamma\gamma \to B_3B_4)$ is the invariant amplitude of the subprocess. Integrating over the invariant mass of the B_3B_4 pair we get

$$\frac{d\sigma}{dp_T} \;=\; \int_{y_0}^{y_{max}} dy \frac{d\sigma}{dp_T dy}\,, \tag{19}$$

with

$$y_0 \;\equiv\; \frac{\sqrt{\frac{s_{\gamma\gamma}}{4}-m^2}}{\sqrt{s_{ee}}}\;\;. \tag{20}$$

This $\frac{d\sigma}{dp_T}$ distribution provides a very useful way for searching for NP, since it not only takes care of the events lost along the beam pipe, but also because its measurement does not require full reconstruction of both final bosons. For the illustrations below we choose $p_T > p_T^{min} = 0.1 TeV/c$.

3 Description of the Boson Pair Production Processes

In this section we summarize the properties of each of the five channels and the way they react to the residual NP lagrangian.

a)$\gamma\gamma \to W^+W^-$

The SM contribution consists of W exchange diagrams in the t and u channels involving the γWW vertex and the $\gamma\gamma WW$ contact term. There is no Higgs exchange at tree level. The W^+W^- production rate is copious and the p_T distributions are given in Figs. (1a,b-4a,b). The NP contributions are induced by the anomalous γWW and $\gamma\gamma WW$ couplings in the case of the operators $\mathcal{O}_W$, $\mathcal{O}_{B\Phi}$, and $\mathcal{O}_{W\Phi}$, and by the anomalous $H\gamma\gamma$ vertex induced by any of $\mathcal{O}_{UW}$, $\mathcal{O}_{UB}$, $\overline{\mathcal{O}}_{UW}$, $\overline{\mathcal{O}}_{UB}$. The SM HWW coupling is also modified by these later four operators.

b)$\gamma\gamma \to ZZ$

There is no SM contribution at tree level. The 1-loop contribution is estimated to be about 100 times smaller than the tree level contribution to W^+W^- [25], so that $\gamma\gamma \to ZZ$ is extremely sensitive to genuine NP effects. There exist no neutral pure gauge anomalous couplings contributing to this process; (they would only appear if higher dimensional operators were considered). Thus, the NP contribution comes from Higgs exchange diagrams in the s, t, u channels induced by anomalous $H\gamma\gamma, H\gamma Z$ and HZZ couplings. They are generated by the six operators $\mathcal{O}_{B\Phi}$, $\mathcal{O}_{W\Phi}$, $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$.

c)$\gamma\gamma \to \gamma\gamma$ and γZ

For these processes also there is no SM contribution at the tree level. NP is only generated by Higgs exchange diagrams due to the four operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$, $\overline{\mathcal{O}}_{UW}$. No SM couplings can appear here. All vertices must be anomalous and at least one must be $H\gamma\gamma$. Thus the other NP operators $\mathcal{O}_W$, $\mathcal{O}_{B\Phi}$ nd $\mathcal{O}_{W\Phi}$ give no contribution at the tree level.

d)$\gamma\gamma \to HH$

Here also there is no SM contribution at the tree level. NP is generated by γ and Z exchange diagrams in the t and u channels, and Higgs exchange in the s-channel, due to anomalous $H\gamma\gamma$ and $H\gamma Z$ couplings generated by the $dim = 6$ operators $\mathcal{O}_{B\Phi}$, $\mathcal{O}_{W\Phi}$, $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$. It is also worth remarking that the Higgs exchange diagram involves also the SM HHH vertex.

4 Sensitivity to the various operators

We now discuss the effect of each of the seven operators treated one by one.

a) The operator $\mathcal{O}_W$ plays a special role because it does not involve scalar fields. It only affects W^+W^- production through terms linear and quadratic in λ_W. The effects of $\mathcal{O}_W$ on the various $\gamma\gamma$ processes are given in Figs. 1a,b for e^+e^- energies of 0.5 and 1. TeV. The sensitivity (already studied in [26]) is given in Table 1.

b) The operators $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ are indistinguishable through these $\gamma\gamma$ processes; (see Fig 2). The amplitudes for $\gamma\gamma \to W^+W^-$ receive both linear and quadratic contributions in f_B or f_W, while the amplitudes for $\gamma\gamma \to ZZ,\ \gamma Z,\ HH$ only get quadratic ones. The highest sensitivity coming from W^+W^- prediction, is given in Table 1 and it is comparable to the sensitivity of $\mathcal{O}_W$.

c) The four operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$, $\overline{\mathcal{O}}_{UW}$ give linear as well as quadratic contributions to the amplitudes for $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to ZZ$ and $\gamma\gamma \to HH$; see Figs. 3,4. Note that the contributions of these operators to the amplitudes for $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to \gamma Z$, which are usually the least sensitive ones, are always quadratic. CP-conserving and CP-violating operators give essentially the same effects in the invariant mass and p_T distributions, except for the HH case. This is because the amplitudes for vector boson production containing the linear terms in the anomalous couplings do not have any appreciable interference with the SM amplitudes. Finally, we also note also that the $\mathcal{O}_{UB}$ contribution may be obtained from the $\mathcal{O}_{UW}$ one by multiplying by the factor c_W^2/s_W^2.

Table 1 summarizes the observability limits expected for each operator by assuming that for W^+W^- production a departure of 5% as compared to the SM prediction in the high p_T range, will be observable. For ZZ channel, the observability limit is set by assuming that a signal of the order of 10^{-2} times the SM W^+W^- rate will be observable. Such an assumption should be reasonable, considering the designed luminosities given in Section 2. These obseravbility limits on the anomalous couplings give essentially lower bounds for the couplings to be observable. Combining these bounds with the unitarity relations [20, 21, 6] we obtain the upper bounds on the related NP scale which are indicated in parentheses in Table 1.

Table 1: Observability limits for the seven couplings. (in parentheses the corresponding scale in TeV is given)				
$2E_e$ (TeV)	$\lvert\lambda_W\rvert$	$\lvert d\rvert$ or d	$\lvert d_B\rvert$ or $\lvert d_B\rvert$	$\lvert f_{B,W}\rvert$
0.5	0.04 (1.7)	0.1 (2.4)	0.04 (4.9)	0.2 (1.8, 1)
1	0.01 (3.5)	0.04 (5.5)	0.01 (10)	0.05 (3.5, 2)
2	0.003 (6.4)	0.01 (21)	0.003 (19)	0.015 (6.5, 3.6)

5 Disentangling the various operators

The purpose of this section is to discuss how one could identify the origin of an anomalous effect detected in one or several of the considered channels. From the analysis made in Sect.3,4 a classification of the seven operators into three different groups has appeared:

- Group 1 contains $\mathcal{O}_W$ which only affects W^+W^-.
- Group 2 contains $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ which also affects predominantly the W^+W^- channel and in a weaker way the ZZ, γZ, HH ones. If the signal in these three channels is too weak to be observable, the disentangling from $\mathcal{O}_W$ is possible by looking at the polarization of the produced $W^{\pm}$. In the $\mathcal{O}_W$ case W^+W^- are produced in (TT) states whereas in the $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ cases it is mainly (LL). There is no way to distinguish the contributions of $\mathcal{O}_{B\Phi}$ from that of $\mathcal{O}_{W\Phi}$ in $\gamma\gamma$ collisios. The discrimination between these two operators requires the use of other processes, like for example $e^+e^- \to W^+W^-$ [9].
- Group 3 contains the four operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$, $\overline{\mathcal{O}}_{UW}$ which mainly affect the channels W^+W^-, ZZ, HH and in a weaker way the $\gamma\gamma$ and γZ ones. The comparison of the effects in W^+W^- and in ZZ production should allow to distinguish this group from the groups 1 and 2. The ZZ final state is mainly (LL) in the group 3, whereas it is (TT) in group 2. The disentangling of $\mathcal{O}_{UW}$ from $\mathcal{O}_{UB}$ can be done by looking at the ratios of the related cross sections. We remark that the linear terms of the WW, ZZ and HH amplitudes for $\mathcal{O}_{UB}$ may be obtained from the corresponding terms for $\mathcal{O}_{UW}$ by multiplying by the factor c_W^2/s_W^2, whereas for the quadratic terms this factor is c_W^4/s_W^4 in $\gamma\gamma$ production and c_W^2/s_W^2 in γZ production.

There is no way to separate the CP-conserving from the CP-violating terms in these spectra. More detailed spin analyses are required, like *e.g.* the search for imaginary parts in final W or Z spin density matrices obseravable through the decay distributions [27] or the measurement of asymmetries associated to linear polarizations of the photon beams [28].

6 Conclusions

We have shown that boson pair production in real $\gamma\gamma$ collisions is an interesting way to search for NP manifestations in the bosonic sector. The $\gamma\gamma$ luminosities provided by laser backscattering at linear e^+e^- colliders should allow to feel NP effects associated to scales up to $\Lambda_{th} = 20TeV$ for $2E_e = 2TeV$. This can be achieved by simply measuring final gauge boson p_T distributions. As no fermionic states are involved, any departure from SM predictions would constitute a clear signal for an anomalous behaviour of the bosonic sector. A comparison of the effects in the various final states WW, ZZ, γZ, $\gamma\gamma$ and HH would already allow a selection among the seven candidate operators which should describe the NP manifestations. Complete disentangling should be possible by analyzing final spin states, i.e. separating $W_T(Z_T)$ from $W_L(Z_L)$ states. Identification of CP violating terms requires full W or Z spin density matrix reconstruction from their decay distributions or analyses with linearly polarized photon beams. The occurrence of anomalous terms in gauge boson couplings or in Higgs boson couplings would be of great interest for tracing back the origin of NP and its basic properties.

Appendix A : Contributions to helicity amplitudes

$\boxed{\gamma\gamma \to \gamma\gamma \text{ and } \gamma\gamma \to \gamma Z}$

Contributions of operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$ to $\gamma\gamma \to \gamma\gamma$

$$
\begin{aligned}
F_{\lambda\lambda'\mu\mu'} &= -\Big\{d_B^2 + d^2\frac{s_W^4}{c_W^4}\Big\}\,\frac{g^2c_W^2 s}{4M_Z^2}\;\;\lambda^2\lambda'^2\mu^2\mu'^2 \\
&\times \;\Big\{\,\frac{s}{s-m_H^2}(1+\lambda\lambda')(1+\mu\mu') + \frac{(\cos\theta-1)}{2}\,(1-\lambda\mu)\,(1-\lambda'\mu')\,\frac{t}{t-m_H^2} \\
&- \;\frac{(\cos\theta+1)}{2}(1-\lambda\mu')\,(1-\lambda'\mu)\frac{u}{u-m_H^2})\,\Big\} \\
&- \;\Big\{\bar{d}_B^2 + \bar{d}^2\,\frac{s_W^4}{c_W^4}\,\Big\}\,\frac{g^2c_W^2 s}{4M_Z^2}\lambda^2\lambda'^2\mu^2\mu'^2 \\
&\times \;\Big\{\;\frac{s}{s-m_H^2}\,(\lambda+\lambda')(\mu+\mu') - \frac{(\cos\theta-1)}{2}\,(\mu-\lambda)\,(\mu'-\lambda')\,\frac{t}{t-m_H^2} \\
&+ \;\frac{(\cos\theta+1)}{2}\,(\mu'-\lambda)\,(\mu-\lambda')\,\frac{u}{u-m_H^2}\,\Big\}
\end{aligned}
\tag{21}
$$

Amplitudes for $\gamma\gamma \to \gamma Z$ are obtained by changing $d[\bar{d}]$ into $(c_W/s_W)d[\bar{d}]$ and $d_B[\bar{d_B}]$ into $-(s_W/c_W)d_B[\bar{d_B}]$.

$\boxed{\gamma\gamma \to W^+W^-}$

Contributions of operators $\mathcal{O}_W$, $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$ to $\gamma\gamma \to W^+W^-$

$$
\begin{aligned}
F_{\lambda\lambda'\mu\mu'} &= e^2\,\frac{\lambda_W\ s}{M_W^2}\,\lambda^2\lambda'^2\mu^2\mu'^2\,\times \\
&\Big\{\ (\delta_{\lambda,\lambda'}\ \delta_{\mu,-\mu'} + \delta_{\lambda,-\lambda'}\ \delta_{\mu,\mu'} - 2\delta_{\lambda,\lambda'}\ \delta_{\mu,\mu'}\ \delta_{\lambda,-\mu} + \\
&+\frac{\lambda_W\ s}{M_W^2}\Big[\ \frac{(1-\cos\theta)\ (3+\cos\theta)}{16}\delta_{\lambda',\mu}\ \delta_{\lambda,-\lambda'}\ \delta_{\mu,-\mu'} \\
&+\frac{3-\cos^2\theta}{8}\delta_{\lambda,\lambda'}\ \delta_{\mu,\mu'}\ \delta_{\lambda,-\mu} + \frac{(1+\cos\theta)(3-\cos\theta)}{16}\delta_{\lambda,\mu}\ \delta_{\lambda',\mu'}\ \delta_{\lambda,-\lambda'}\ \Big]\ \Big\} - \\
&-\frac{g^2c_W^2d_B}{4M_W^2}\,\frac{s^2}{(s-m_H^2)}\,(1+\lambda\lambda')\ (1-\mu^2)\ (1-\mu'^2)\lambda^2\lambda'^2 \\
-\ &\frac{g^2s_W^2d}{4M_W^2}\,\frac{s^2}{(s-m_H^2)}\,(1+\lambda\lambda')\ \Big[\ (1-\mu^2)(1-\mu'^2) + \ d\ \mu^2\mu'^2(1+\mu\mu')\ \Big]\ \lambda^2\lambda'^2 \\
+\ &i\,\frac{g^2c_W^2\bar{d}_B}{4M_W^2}\,\frac{s^2}{(s-m_H^2)}\,(\lambda+\lambda')\ (1-\mu^2)(1-\mu'^2)\lambda^2\lambda'^2 \qquad (22)\\
+\ &i\,\frac{g^2s_W^2\bar{d}}{4M_W^2}\,\frac{s^2}{(s-m_H^2)}\,(\lambda+\lambda')\ \Big[\ (1-\mu^2)\ (1-\mu'^2)\ +\ i\ \bar{d}\ \mu^2\mu'^2(\mu+\mu')\ \Big]\ \lambda^2\lambda'^2
\end{aligned}
$$

Contributions of operators $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ to $\gamma\gamma \to W^+W^-$

$$
\begin{aligned}
F_{+--+} &= F_{-++-} = -e^2(f_B^2+f_W^2)\frac{(\cos\theta-1)\ s}{32M_W^2} \\
F_{+-+-} &= F_{-+-+} = e^2(f_B^2+f_W^2)\frac{(\cos\theta+1)\ s}{32M_W^2} \\
F_{+-00} &= F_{-+00} = F_{++--} = F_{--++} = e^2(f_B^2+f_W^2)\frac{s}{16M_W^2} \\
F_{++00} &= F_{--00} = -2e^2(f_B^2+f_W^2)\frac{s}{16M_W^2} - e^2(f_B+f_W)\frac{s}{2M_W^2} \qquad (23)
\end{aligned}
$$

$\boxed{\gamma\gamma \to ZZ}$

Contributions of operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$ to $\gamma\gamma \to ZZ$

$$
\begin{aligned}
F_{\lambda\lambda'\mu\mu'} &= -\frac{g^2}{4M_Z^2}\,[d_B + d\,\frac{s_W^2}{c_W^2}]\,\frac{s^2}{(s-m_H^2)}\,(1+\lambda\lambda')\,(1-\mu^2)\,(1-\mu'^2)\lambda^2\lambda'^2 \\
&\quad -\frac{g^2 s_W^2 c_W^2 s}{4M_W^2}(d_B^2+d^2)\lambda^2\lambda'^2\mu^2\mu'^2\,\Big\{\,(\frac{s}{(s-m_H^2)})(1+\lambda\lambda')\,((1+\mu\mu') \\
&\quad +\frac{(\cos\theta-1)}{2}(1-\lambda\mu)\,(1-\lambda'\mu')\,\frac{t}{t-m_H^2} \\
&\quad -\frac{(\cos\theta+1)}{2}(1-\lambda\mu')\,(1-\lambda'\mu)\,\frac{u}{u-m_H^2}\,\Big\} \\
&\quad +i\,\frac{g^2}{4M_W^2}\,[\bar{d_B}\,c_W^2+\bar{d}\,s_W^2]\,\frac{s^2}{(s-m_H^2)}\,(\lambda+\lambda')\lambda^2\lambda'^2(1-\mu^2)\,(1-\mu'^2) \\
&\quad -(\bar{d}^2+\bar{d_B}^2)c_W^2 s_W^2\,\frac{g^2}{4M_W^2}\,\frac{s^2}{(s-m_H^2)}(\mu+\mu')\mu^2\mu'^2\,(\lambda+\lambda')\lambda^2\lambda'^2 \\
&\quad +\frac{g^2 s_W^2 c_W^2}{16M_W^2}\,[\bar{d_B^2}+\bar{d}^2]\,s^2\,\Big\{\,\frac{(\cos\theta-1)^{\,2}}{t-m_H^2}(\mu-\lambda)\,(\mu'-\lambda') \\
&\quad +\frac{(\cos\theta+1)^{\,2}}{u-m_H^2}(\mu'-\lambda)\,(\mu-\lambda')\,\Big\}\,\lambda^2\lambda'^2\mu^2\mu'^2
\end{aligned}
\tag{24}
$$

Contributions of operators $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ to $\gamma\gamma \to ZZ$

$$
\begin{aligned}
F_{+--+} &= F_{-++-} = -g'^2\,(f_B^2+f_W^2)\,\frac{(\cos\theta-1)^{\,2}s^2}{64M_W^2(t-m_H^2)} \\
F_{+-+-} &= F_{-+-+} = -g'^2\,(f_B^2+f_W^2)\,\frac{(\cos\theta+1)^{\,2}s^2}{64M_W^2(u-m_H^2)} \\
F_{++--} &= F_{--++} = -g'^2\,(f_B^2+f_W^2)\,\frac{s^2}{64M_W^2}\,\Big\{\,\frac{(\cos\theta-1)^{\,2}}{(t-m_H^2)}+\frac{(\cos\theta+1)^{\,2}}{(u-m_H^2)}\,\Big\}
\end{aligned}
\tag{25}
$$

$$\boxed{\gamma\gamma \to H\ H}$$

Contributions of operators $\mathcal{O}_{UB}$, $\mathcal{O}_{UW}$, $\overline{\mathcal{O}}_{UB}$ and $\overline{\mathcal{O}}_{UW}$ to $\gamma\gamma \to H\ H$

$$\begin{aligned} F_{\lambda\lambda'} &= -\lambda^2\lambda'^2 g^2 \left[\frac{(c_W^2\ d_B^2 + s_W^2\ d^2)\ s}{2M_W^2}\,(1+3\lambda\lambda') + \frac{(c_W^2\ d_B + s_W^2\ d)\ s}{4M_W^2}\,(1+\lambda\lambda') \right] \\ &\quad +\lambda^2\lambda'^2 g^2 \left[\frac{(c_W^2\ \bar{d}_B^2 + s_W^2\ \bar{d}^2)\ s}{2M_W^2}\,(3+\lambda\lambda') + i\frac{(c_W^2\ \bar{d}_B + s_W^2\ \bar{d})\ s}{4M_W^2}\,(\lambda+\lambda') \right] \end{aligned} \quad (26)$$

Contributions of operators $\mathcal{O}_{B\Phi}$, $\mathcal{O}_{W\Phi}$ to $\gamma\gamma \to H\ H$

$$F_{--} = -2F_{-+} = -e^2(f_B^2 + f_W^2)\,\frac{s}{8c_W^2 M_W^2} \quad (27)$$

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Figure Captions

Fig.1 Sensitivity to the operator $\mathcal{O}_W$ in $\gamma\gamma \to W^+W^-$. Transverse momentum (p_T) distribution $d\sigma/dp_T$ (a) at 0.5 TeV, (b) at 1 TeV.

Fig.2 Sensitivity to the operators $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ in $\gamma\gamma \to W^+W^-$, ZZ, HH. (a), (b), same captions.

Fig.3 Sensitivity to the operators $\mathcal{O}_{UW}$ and $\overline{\mathcal{O}}_{UW}$ in $\gamma\gamma \to W^+W^-$, ZZ, γZ, $\gamma\gamma$, HH. (a), (b), same captions.

Fig.4 Sensitivity to the operators $\mathcal{O}_{UB}$ and $\overline{\mathcal{O}}_{UB}$ in $\gamma\gamma \to W^+W^-$, ZZ, γZ, $\gamma\gamma$, HH. (a), (b), same captions.

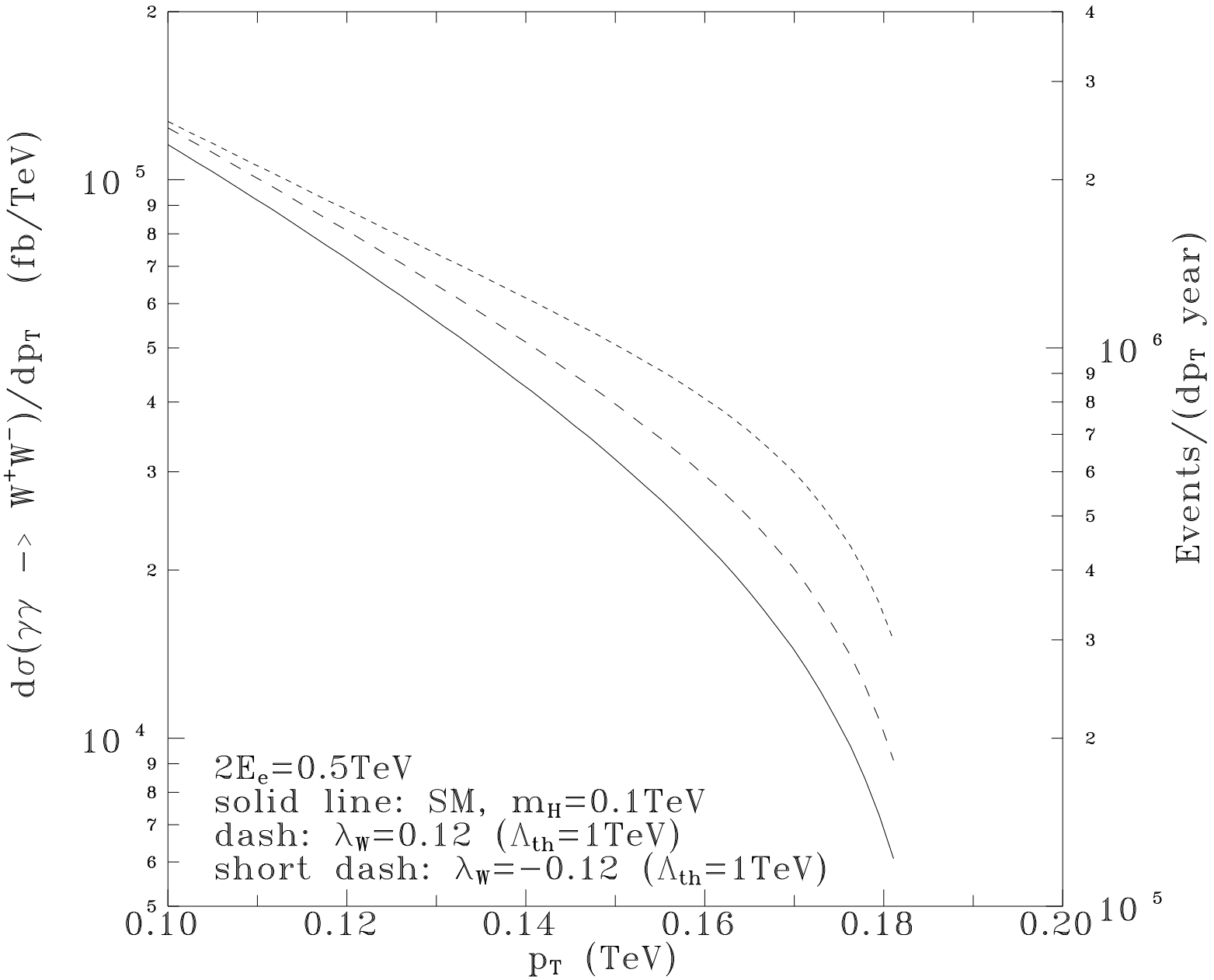
$d\sigma(\gamma\gamma \rightarrow W^+W^-)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
$2E_e$=0.5TeV
solid line: SM, m_H=0.1TeV
dash: λ_W=0.12 (Λ_{th}=1TeV)
short dash: λ_W=−0.12 (Λ_{th}=1TeV)

Fig 1a

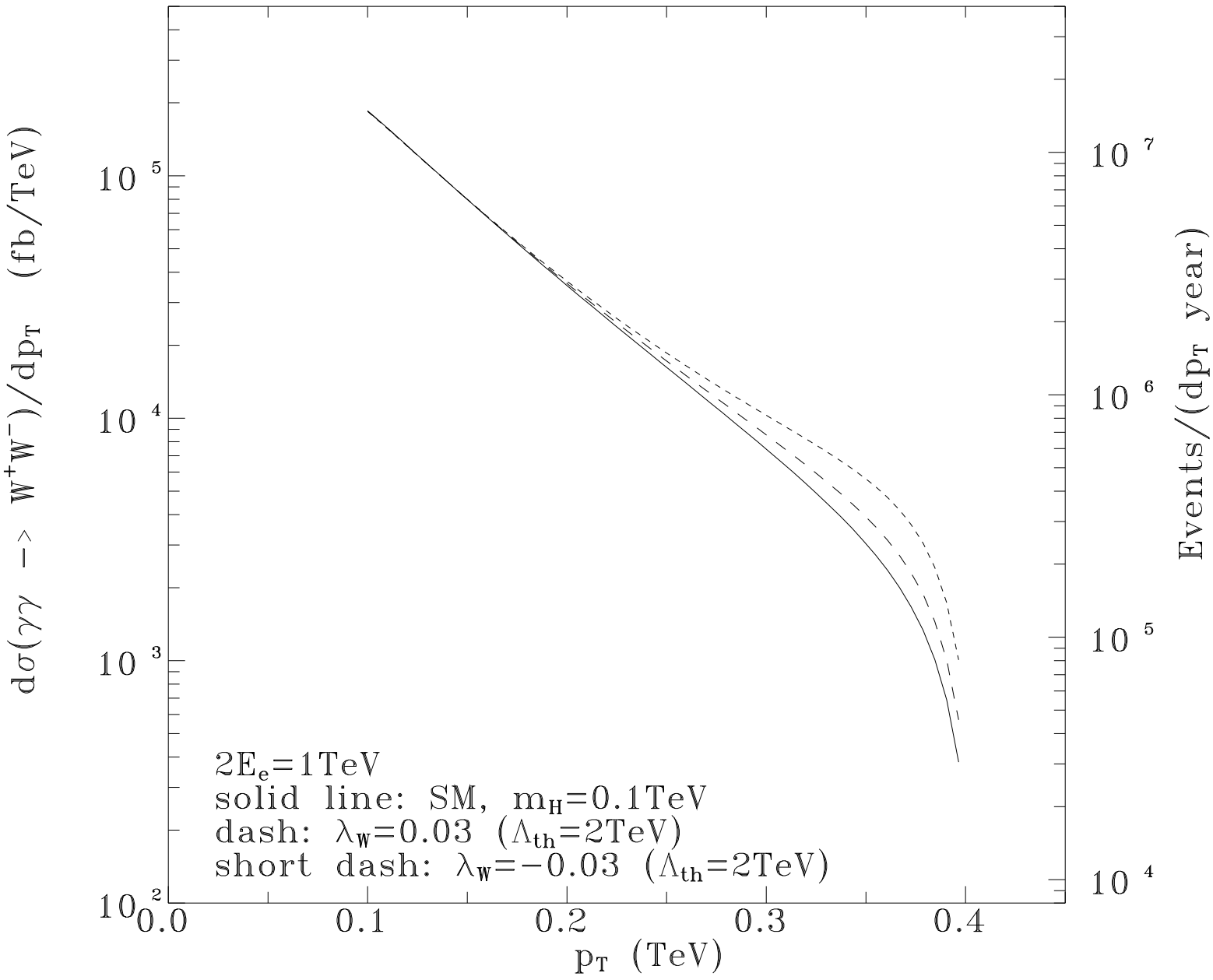
$d\sigma(\gamma\gamma \rightarrow W^+W^-)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
$2E_e$=1TeV
solid line: SM, m_H=0.1TeV
dash: λ_W=0.03 (Λ_{th}=2TeV)
short dash: λ_W=−0.03 (Λ_{th}=2TeV)

Fig 1b

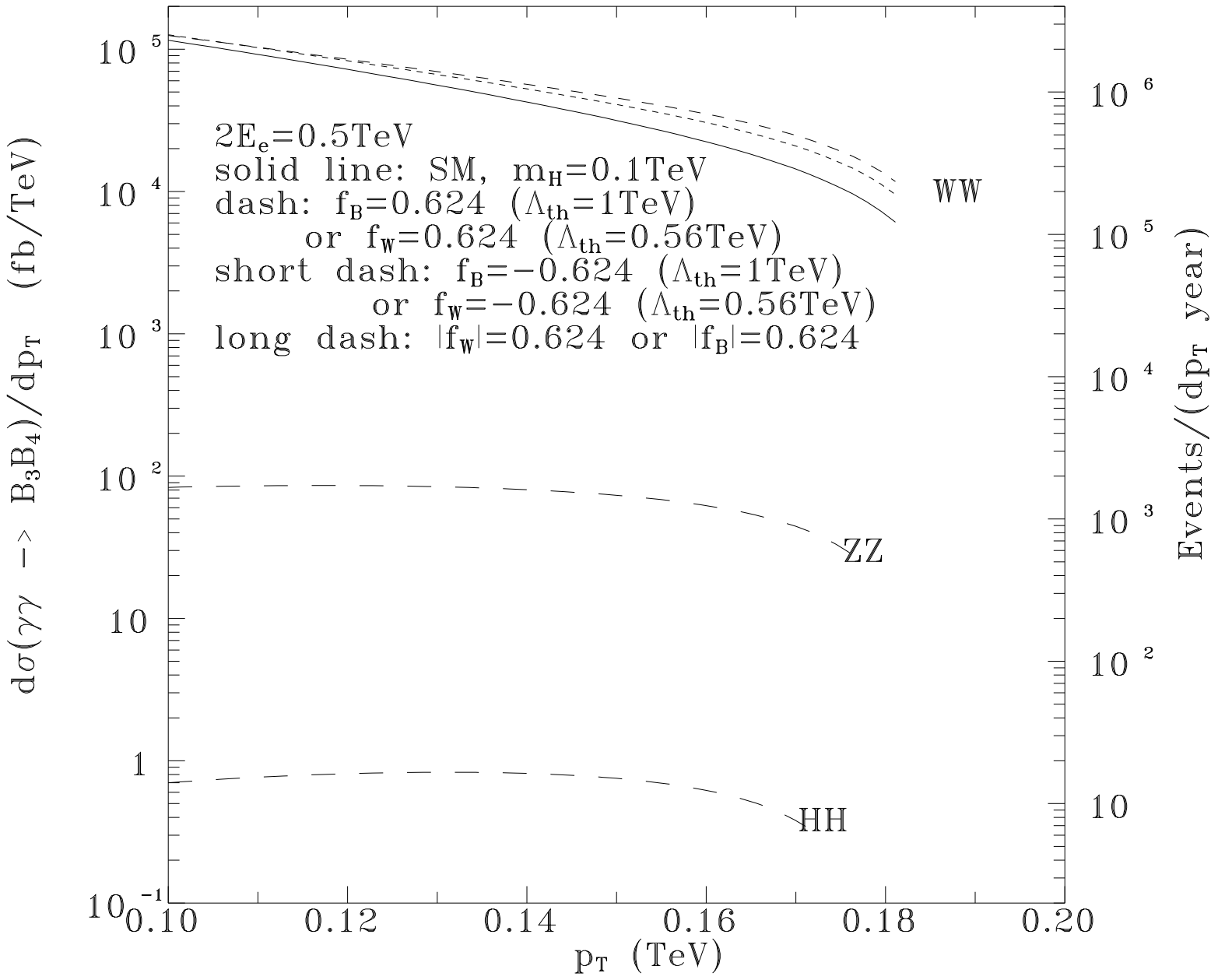
$2E_e$=0.5TeV
solid line: SM, m_H=0.1TeV
dash: f_B=0.624 (Λ_{th}=1TeV)
or f_W=0.624 (Λ_{th}=0.56TeV)
short dash: f_B=−0.624 (Λ_{th}=1TeV)
or f_W=−0.624 (Λ_{th}=0.56TeV)
long dash: $|f_W|$=0.624 or $|f_B|$=0.624
WW
ZZ
HH
$d\sigma(\gamma\gamma \rightarrow B_3B_4)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
0.10
0.12
0.14
0.16
0.18
0.20

Fig 2a

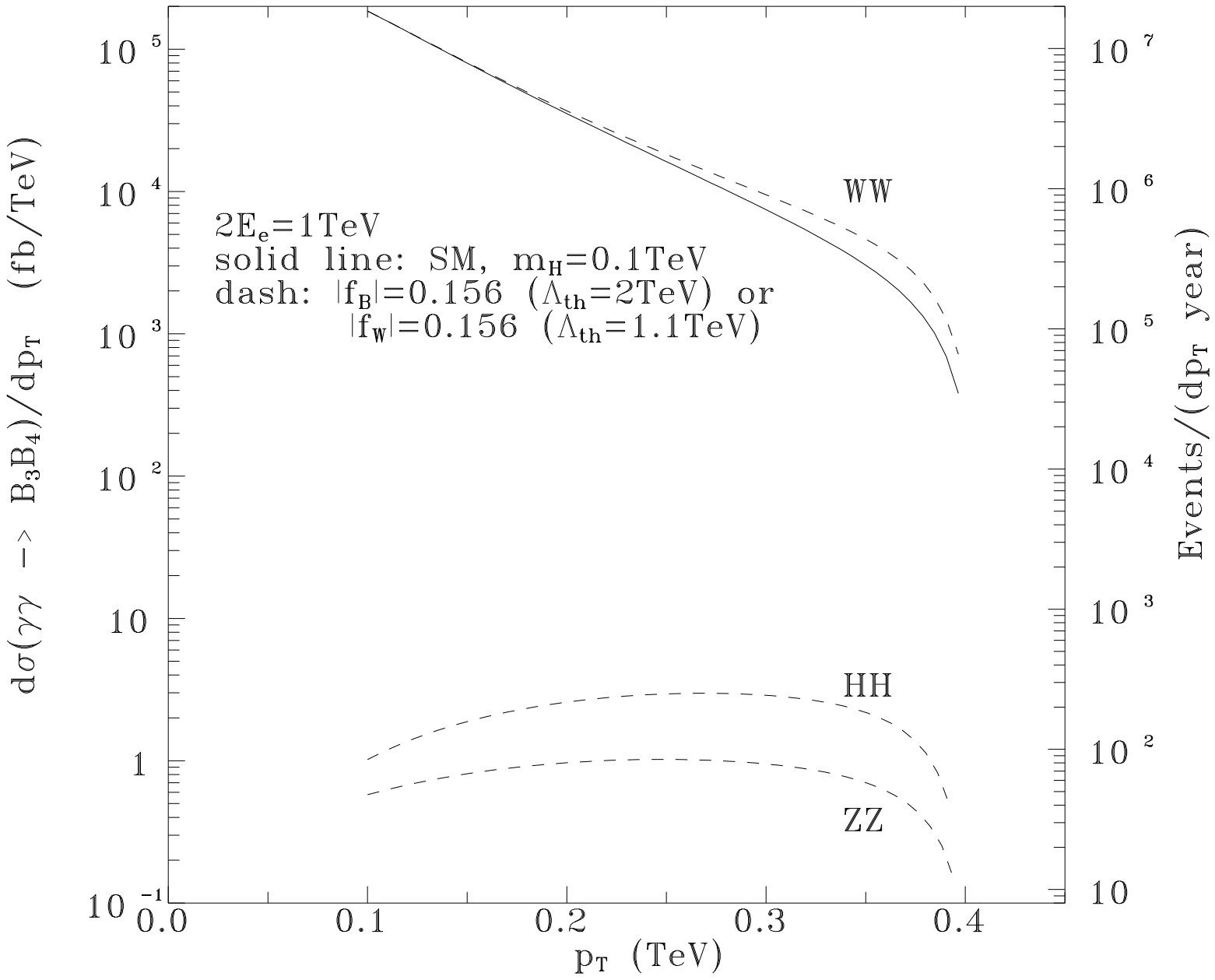
$2E_e$=1TeV
solid line: SM, m_H=0.1TeV
dash: $|f_B|$=0.156 (Λ_{th}=2TeV) or
$|f_W|$=0.156 (Λ_{th}=1.1TeV)
WW
HH
ZZ
$d\sigma(\gamma\gamma \rightarrow B_3B_4)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
0.0
0.1
0.2
0.3
0.4

Fig 2b

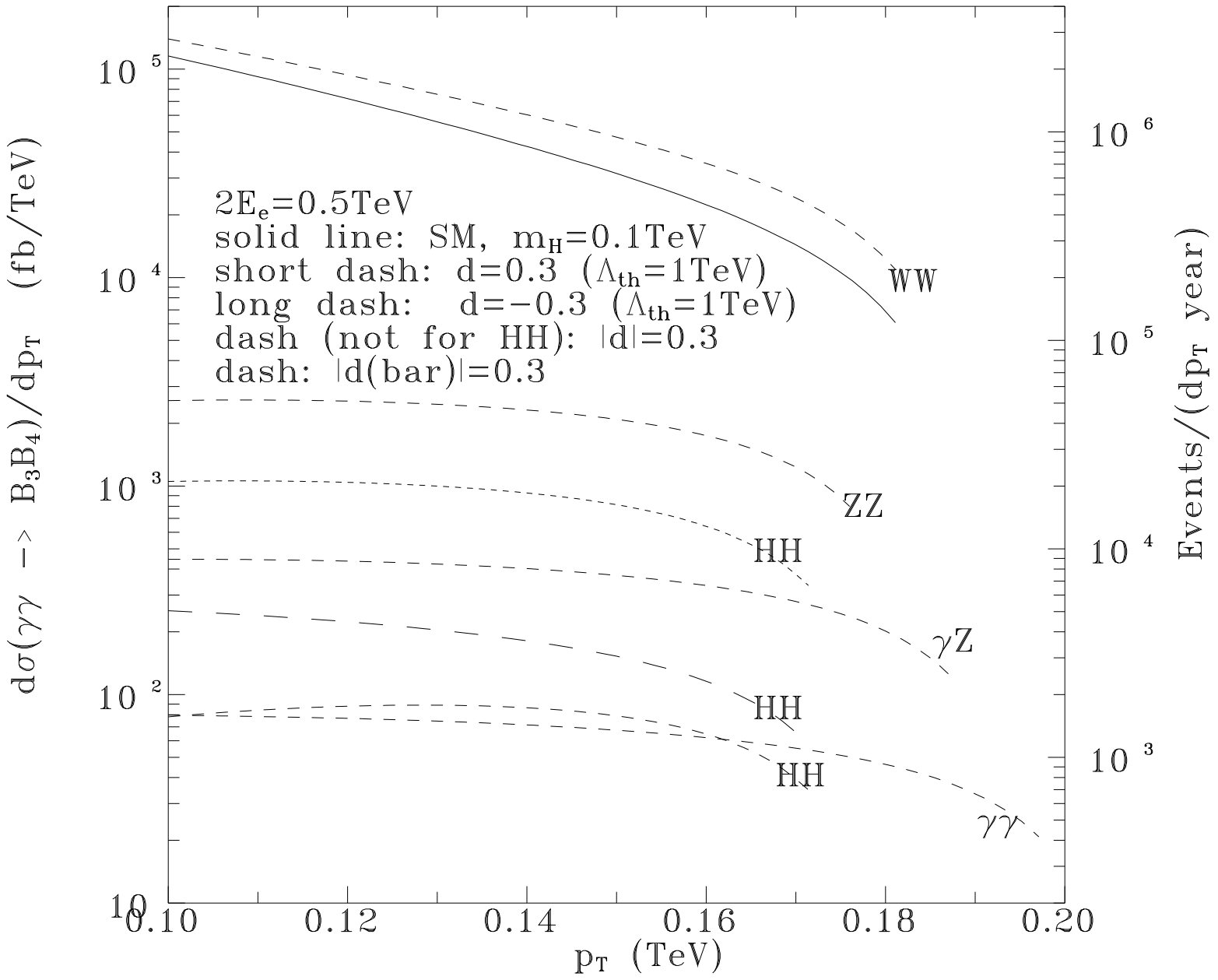
$2E_e$=0.5TeV
solid line: SM, m_H=0.1TeV
short dash: d=0.3 (Λ_{th}=1TeV)
long dash: d=−0.3 (Λ_{th}=1TeV)
dash (not for HH): |d|=0.3
dash: |d(bar)|=0.3
WW
ZZ
HH
γZ
HH
HH
$\gamma\gamma$
$d\sigma(\gamma\gamma \rightarrow B_3B_4)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^5
10^4
10^3
10^2
10
10^6
10^5
10^4
10^3
0.10
0.12
0.14
0.16
0.18
0.20

Fig 3a

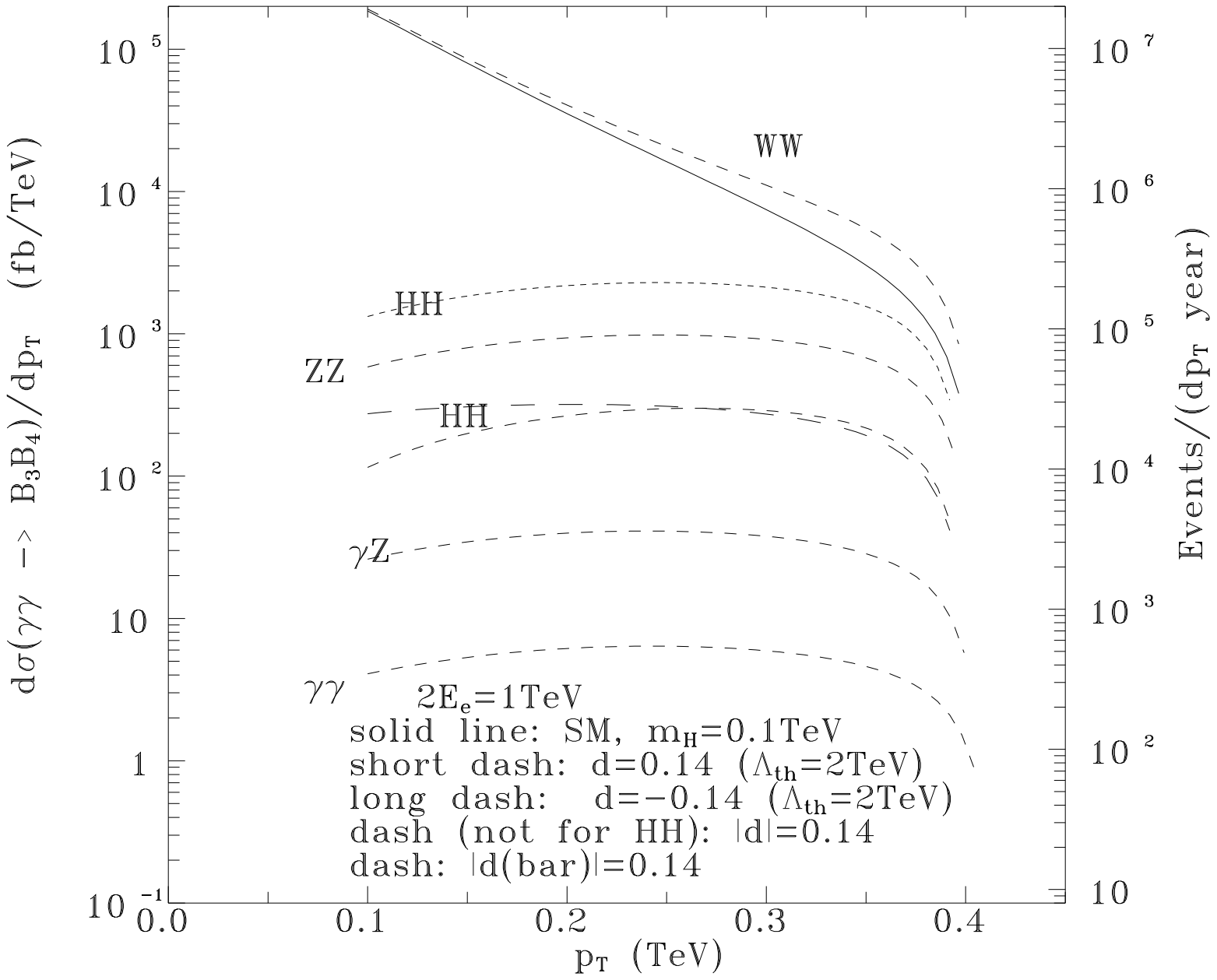
WW
HH
ZZ
HH
γZ
γγ
2E_e=1TeV
solid line: SM, m_H=0.1TeV
short dash: d=0.14 (Λ_th=2TeV)
long dash: d=−0.14 (Λ_th=2TeV)
dash (not for HH): |d|=0.14
dash: |d(bar)|=0.14
dσ(γγ −> B_3B_4)/dp_T (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^5
10^4
10^3
10^2
10
1
10^-1
10^7
10^6
10^5
10^4
10^3
10^2
10
0.0
0.1
0.2
0.3
0.4

Fig 3b

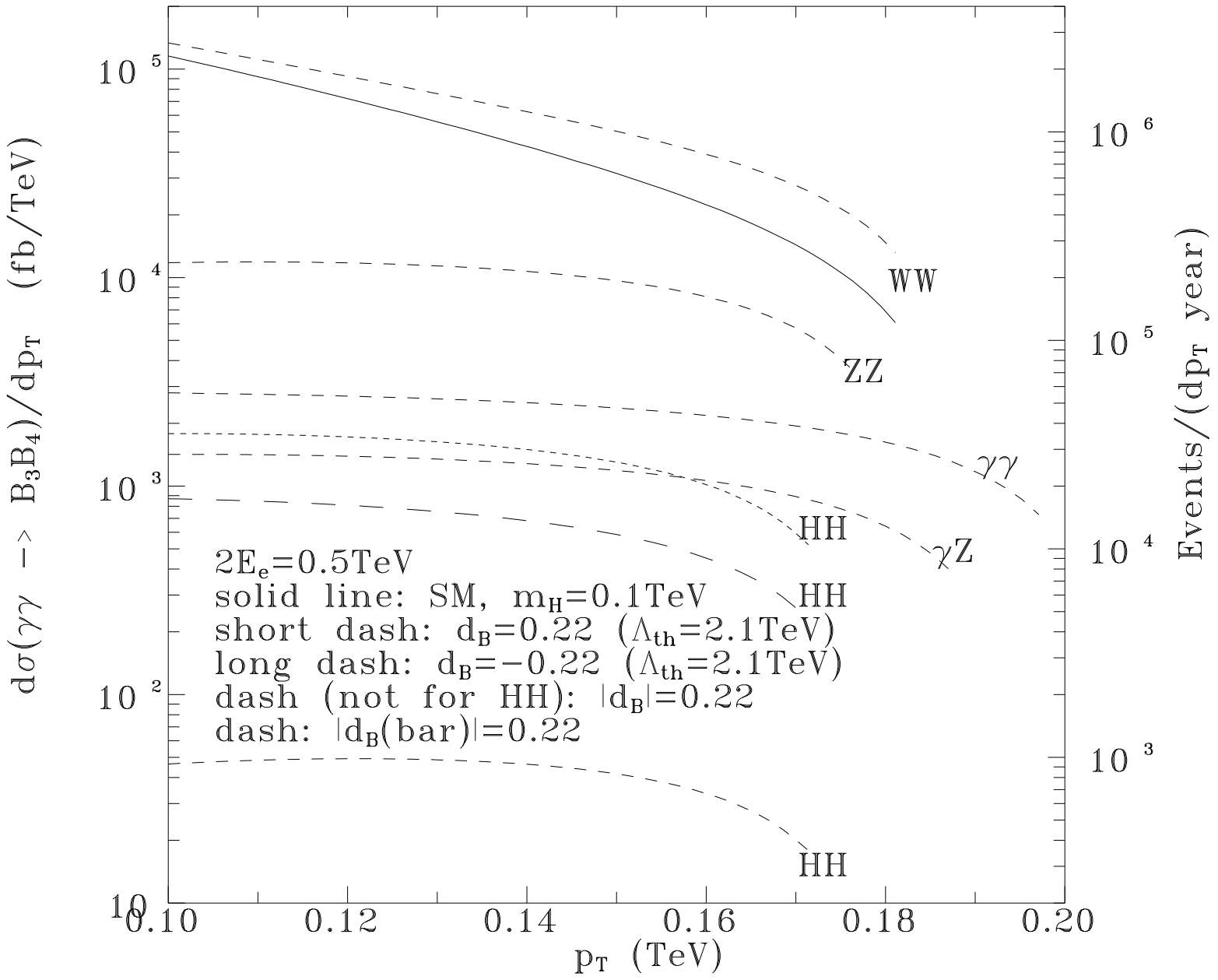
$d\sigma(\gamma\gamma \rightarrow B_3B_4)/dp_T$ (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^5
10^4
10^3
10^2
10
10^6
10^5
10^4
10^3
0.10
0.12
0.14
0.16
0.18
0.20
WW
ZZ
$\gamma\gamma$
χZ
HH
HH
HH
$2E_e$=0.5TeV
solid line: SM, m_H=0.1TeV
short dash: d_B=0.22 (Λ_{th}=2.1TeV)
long dash: d_B=−0.22 (Λ_{th}=2.1TeV)
dash (not for HH): $|d_B|$=0.22
dash: $|d_B(bar)|$=0.22

Fig 4a

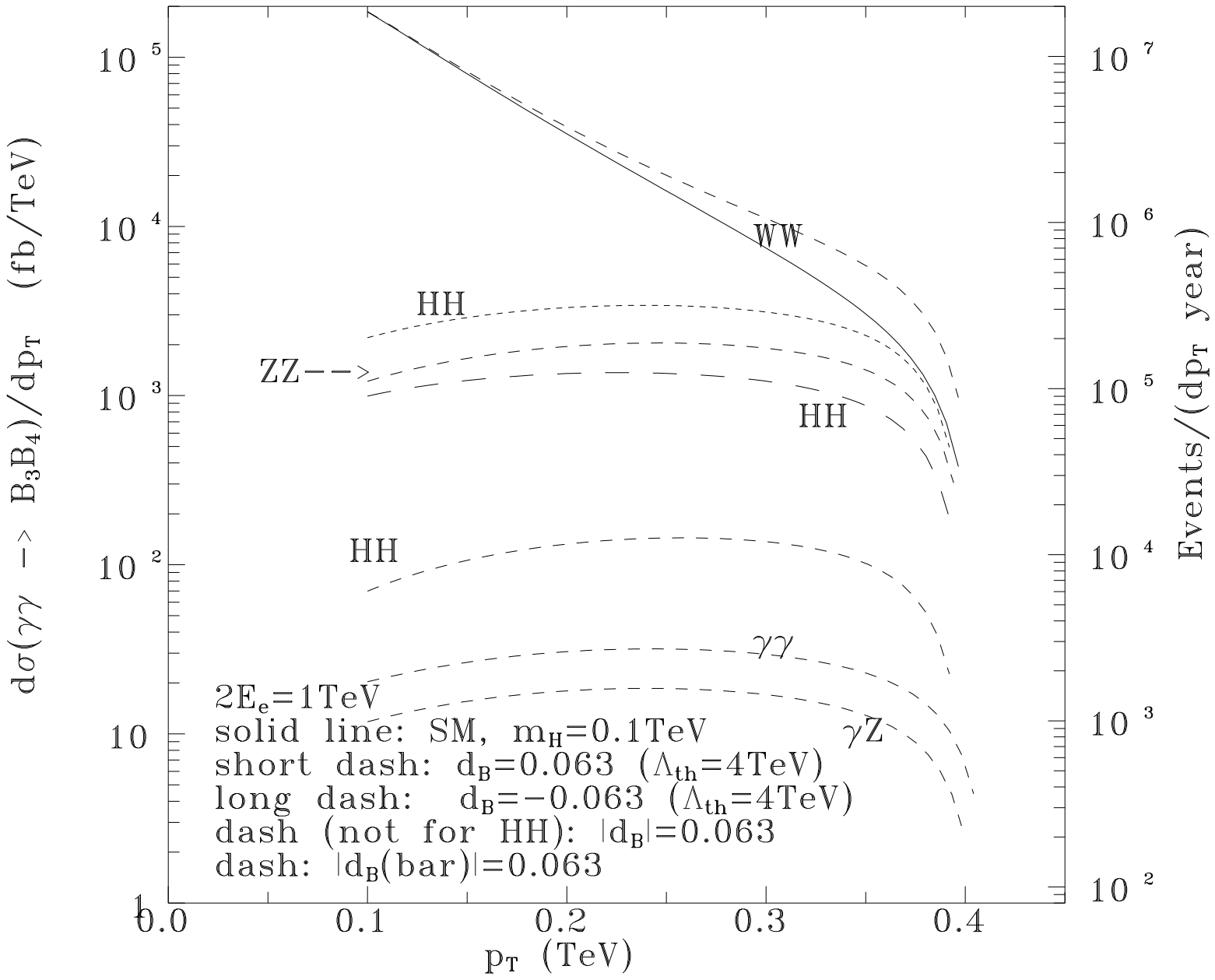
WW
HH
ZZ-->
HH
HH
γγ
γZ
2E_e=1TeV
solid line: SM, m_H=0.1TeV
short dash: d_B=0.063 (Λ_th=4TeV)
long dash: d_B=−0.063 (Λ_th=4TeV)
dash (not for HH): |d_B|=0.063
dash: |d_B(bar)|=0.063
dσ(γγ -> B_3B_4)/dp_T (fb/TeV)
Events/(dp_T year)
p_T (TeV)
10^5
10^4
10^3
10^2
10
1
10^7
10^6
10^5
10^4
10^3
10^2
0.0
0.1
0.2
0.3
0.4

Fig 4b